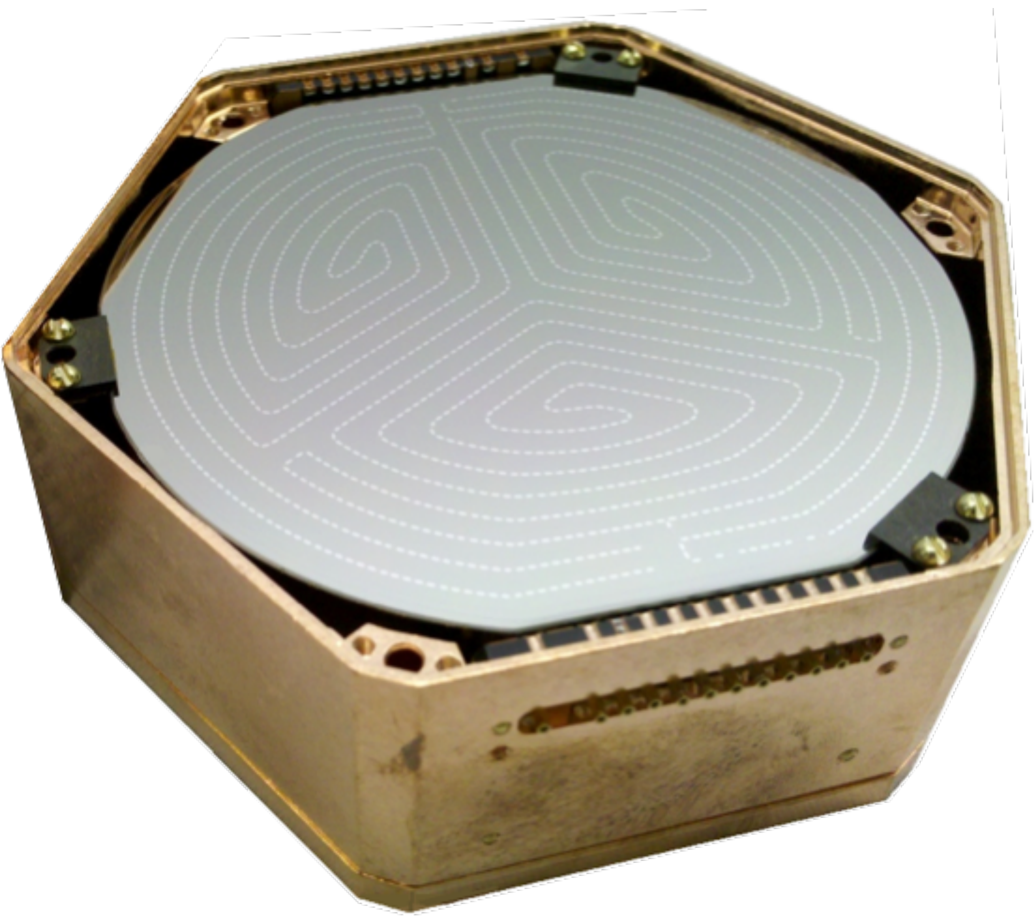
Building a Light Mass Detector



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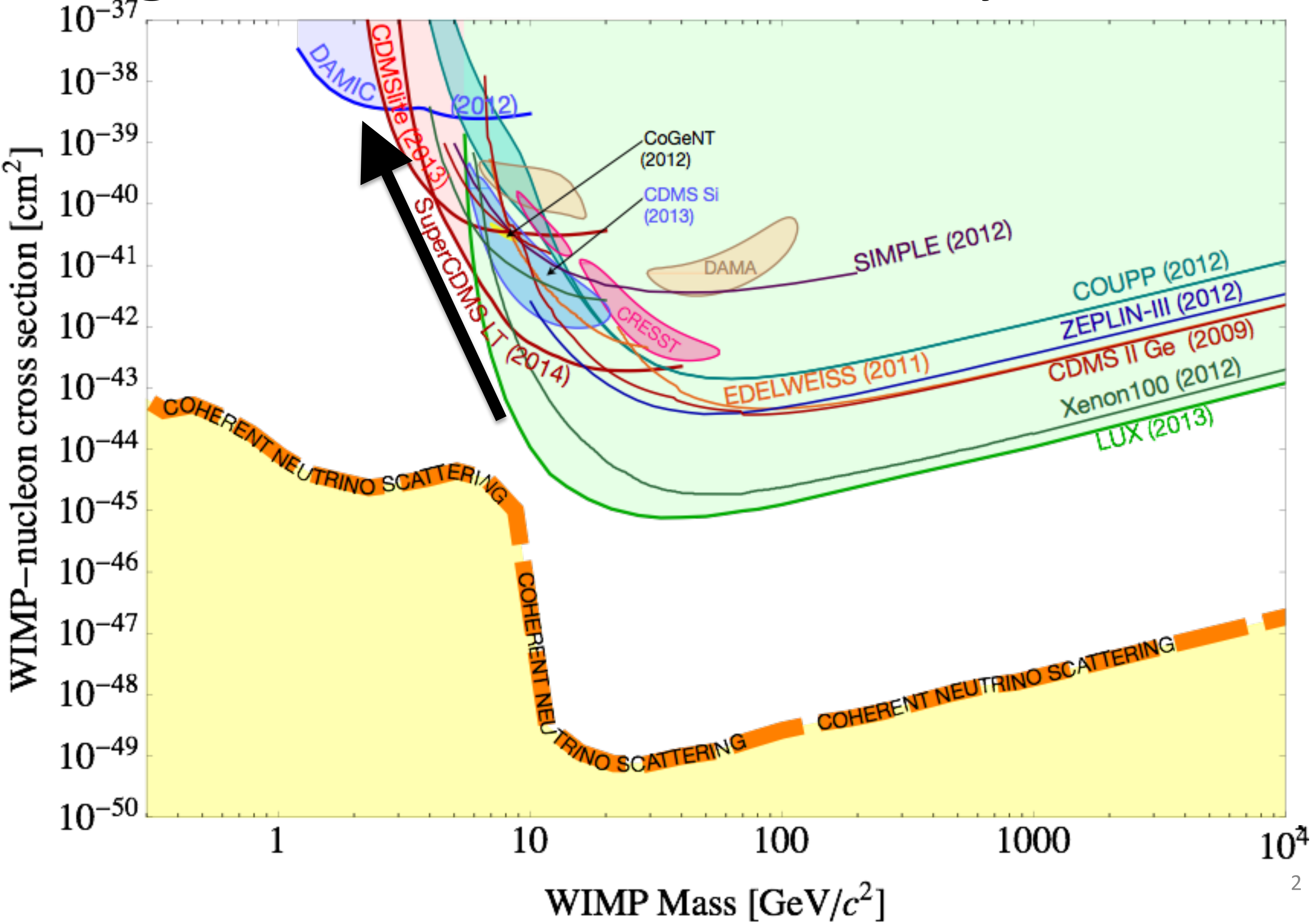
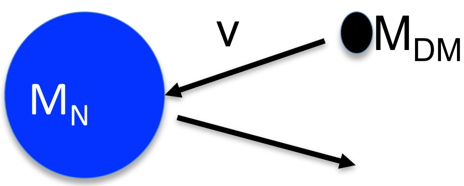
University of California Berkeley

Phys 290e
15/09/16

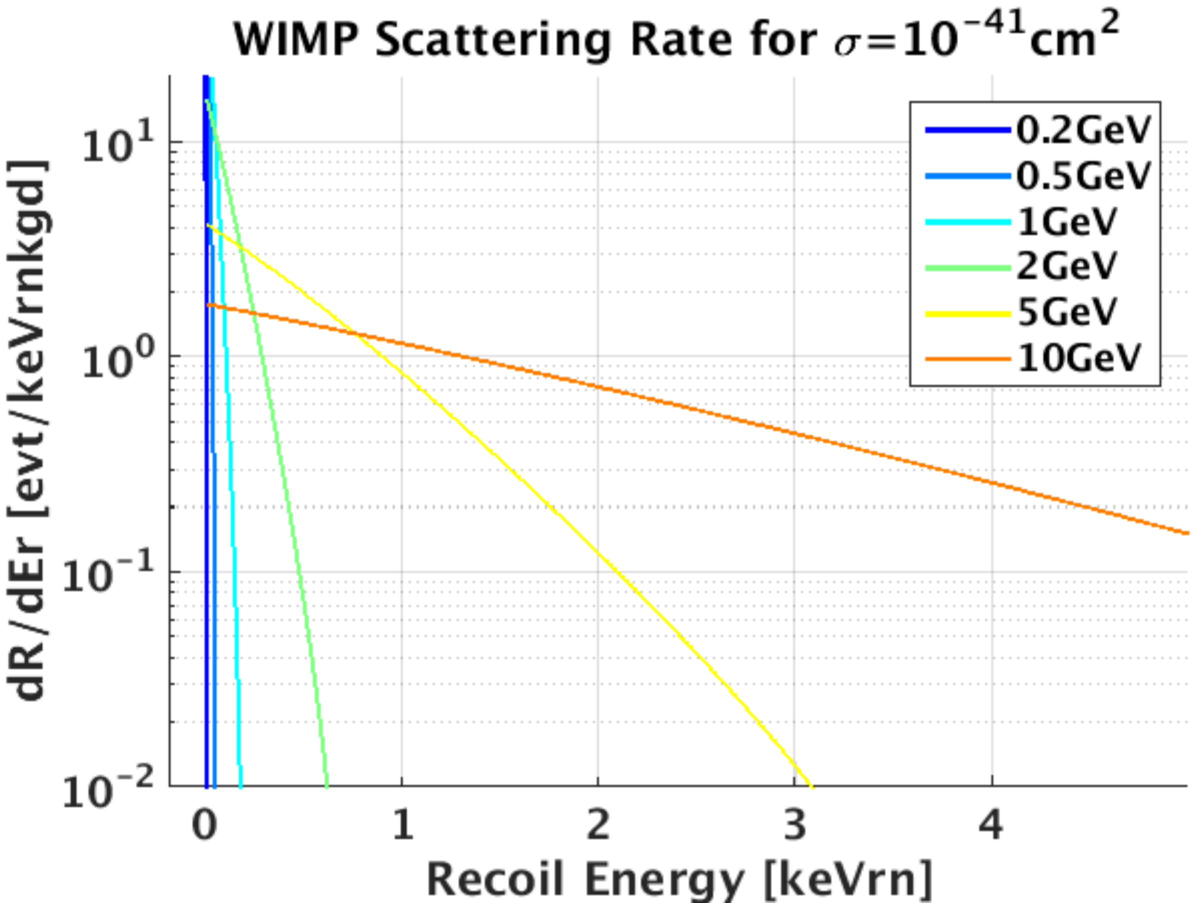
Light Mass DM Limits: Why So Bad?



The low-mass WIMP Direct Detection Challenge

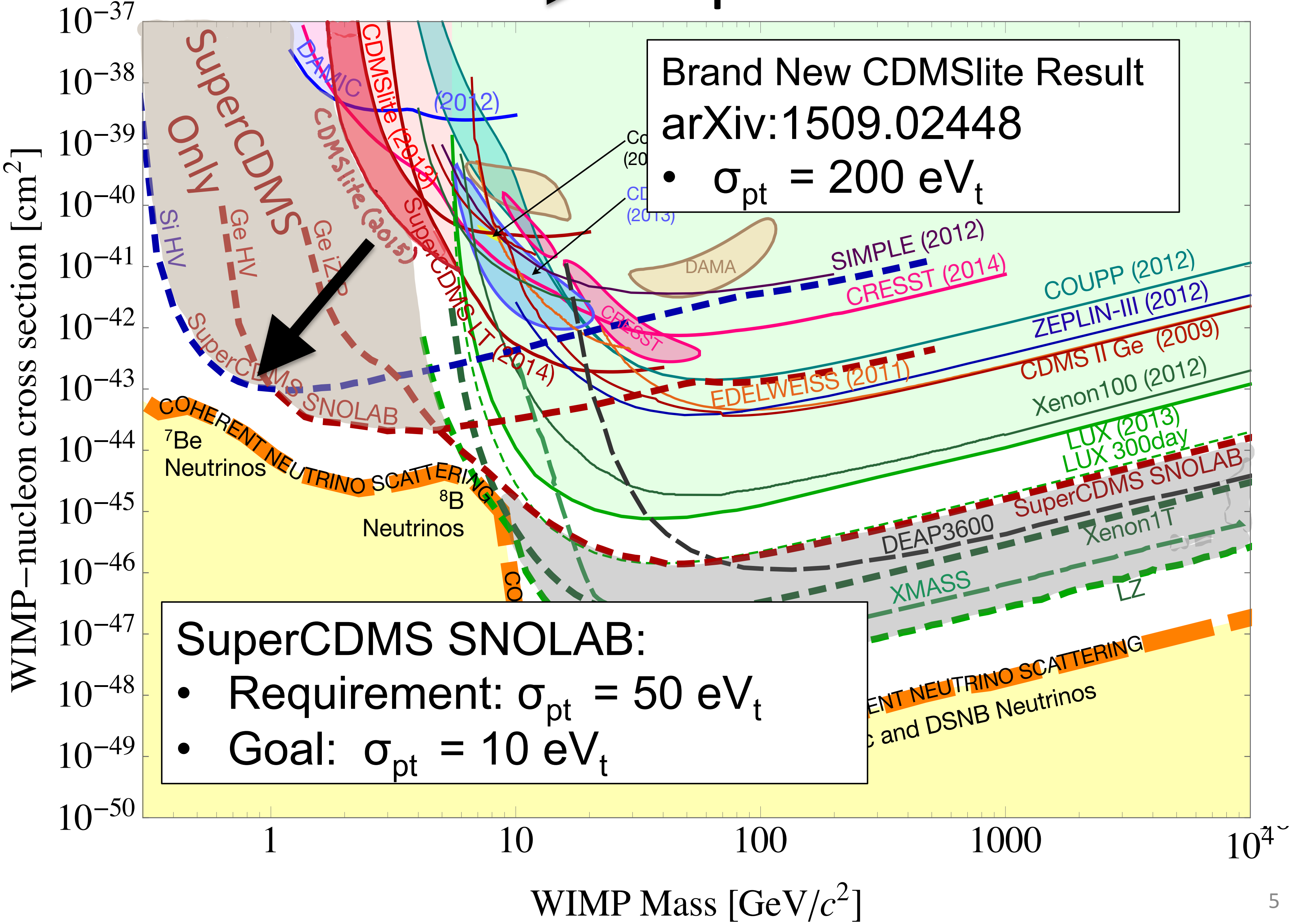


$$\Delta E = \frac{\Delta P^2}{2M_N} \sim \frac{2M_{DM}^2 v^2}{M_N}$$



#1 Design Driver for a Light Mass Dark Matter Detector : A Massive Detector with Amazing Energy Sensitivity

CDMSlite → SuperCDMS SNOLAB



Brand New CDMSlite Result

arXiv:1509.02448

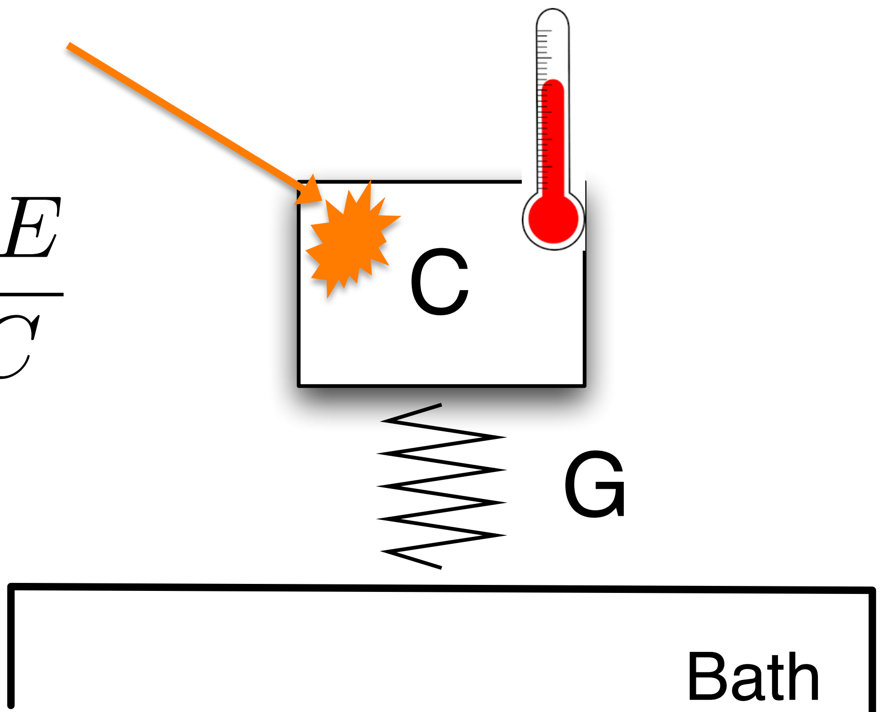
- σ_{pt} = 200 eV_t

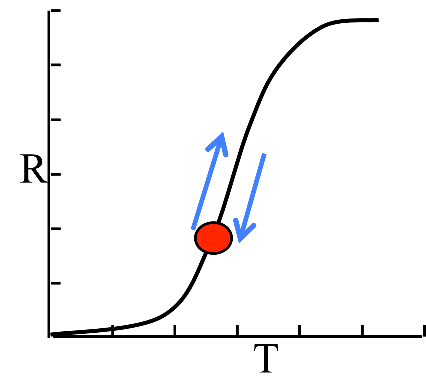
SuperCDMS SNOLAB:

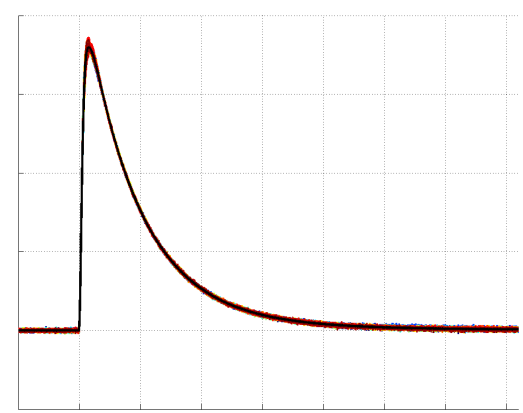
- Requirement: σ_{pt} = 50 eV_t
- Goal: σ_{pt} = 10 eV_t

Calorimeter Basics

$$\delta T = \frac{\delta E}{C}$$



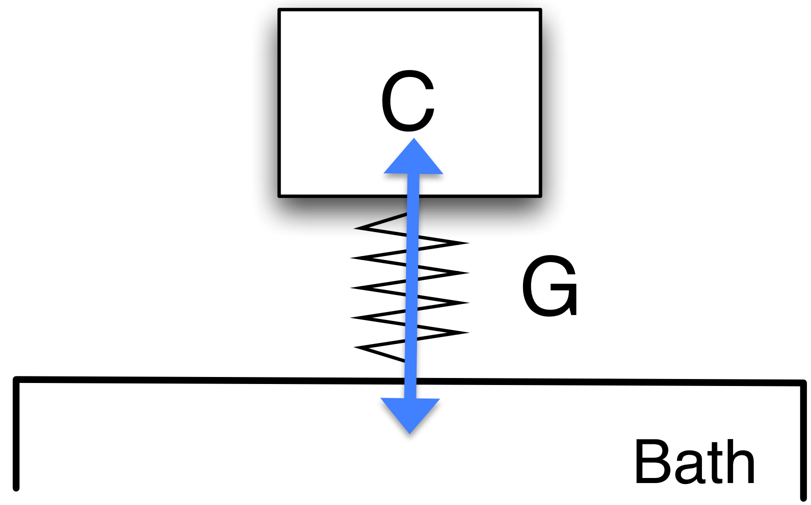




Calorimeter Sensitivity

$$< E > = \sum_i E_i \frac{e^{-\beta E_i}}{\sum_j e^{-\beta E_j}}$$

$$= \frac{\sum E_i e^{-\beta E_i}}{\sum_j e^{-\beta E_j}} = \frac{\frac{-\partial Z}{\partial \beta}}{Z}$$



$$\sigma^2_{<E>} = \sum_i (E_i - < E >)^2 \frac{e^{-\beta E_i}}{\sum_j e^{-\beta E_j}}$$

$$= \frac{\sum_i E_i^2 e^{-\beta E_i}}{\sum_j e^{-\beta E_j}} - < E >^2$$

$$= -\frac{\partial < E >}{\partial \beta} = \frac{\partial < E >}{\partial T} k_b T^2 = C k_b T^2$$

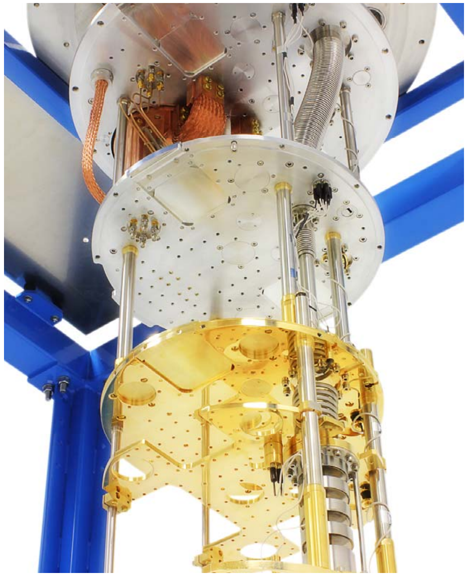
~ Intrinsic Thermal Noise of Calorimeters

Calorimeter Optimization

$$\sigma^2_{<E>} = C k_b T^2$$

- Minimize T
  - Dilution Refrigerators can cool detectors to 5mK
- Minimize C
  - ~~Small Volume~~
  - Low T
  - Insulators

} Freeze out



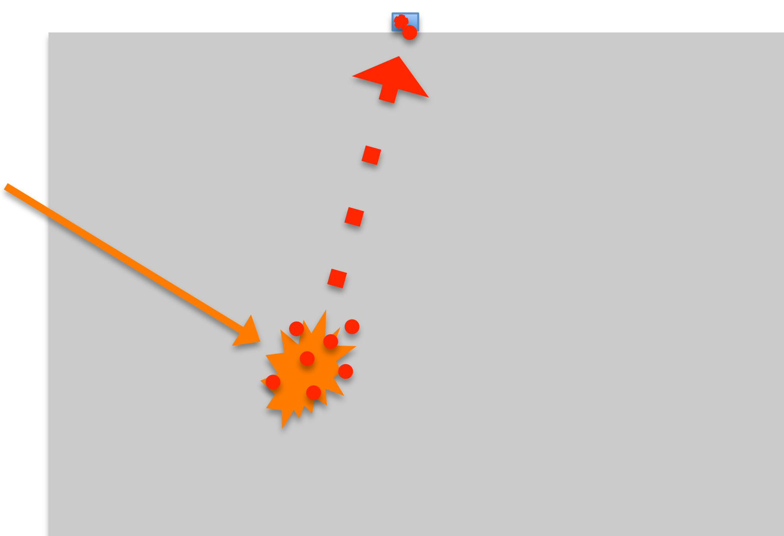
$$C = \frac{\partial E}{\partial T} = \frac{\partial E}{\partial \beta}\frac{\partial \beta}{\partial T} = \frac{\partial E}{\partial \beta}\frac{-1}{k_b T^2}$$

$$= \left(\frac{\sum_i E_i^2 e^{-\beta E_i}}{\sum_j e^{-\beta E_j}} - <E>^2\right)\frac{1}{k_b T^2}$$

States with $E_i >> k_b T$ aren't thermally accessible, and don't contribute to the heat capacity

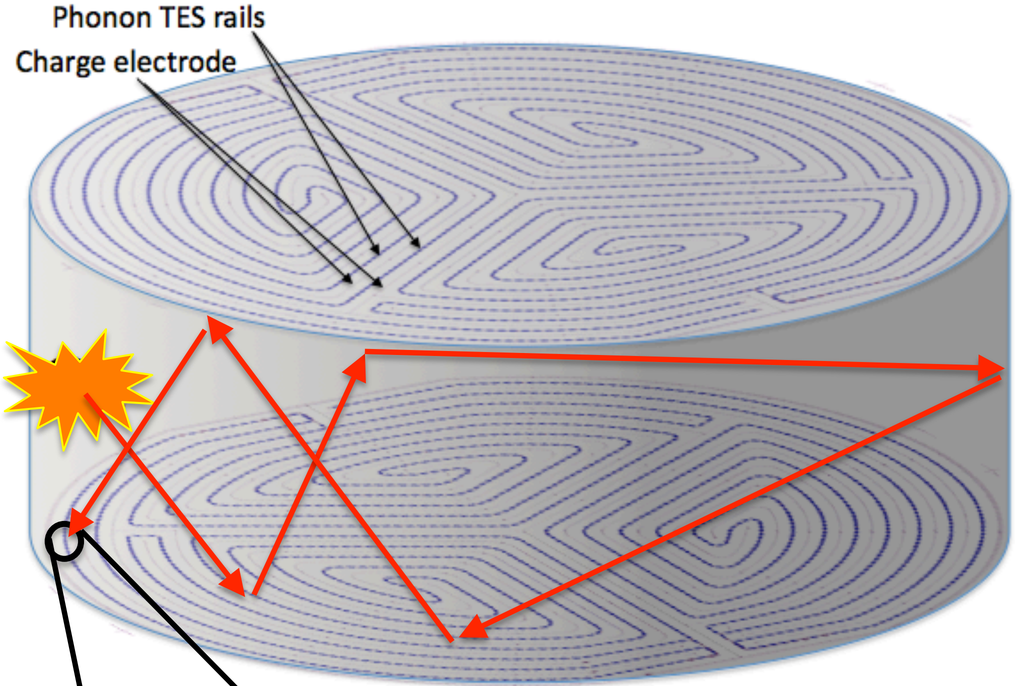
Excitation Collection and Concentration

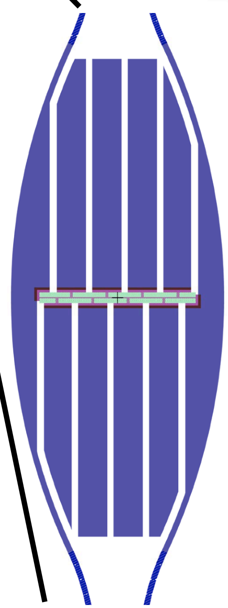
$$\sigma^2_{<E>} = C k_b T^2$$



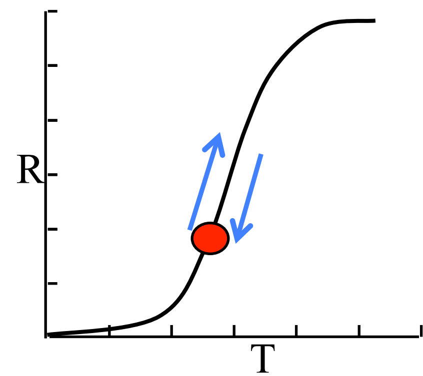
Collect non-thermal excitations in a sensor with small volume & small heat capacity before they can thermalize

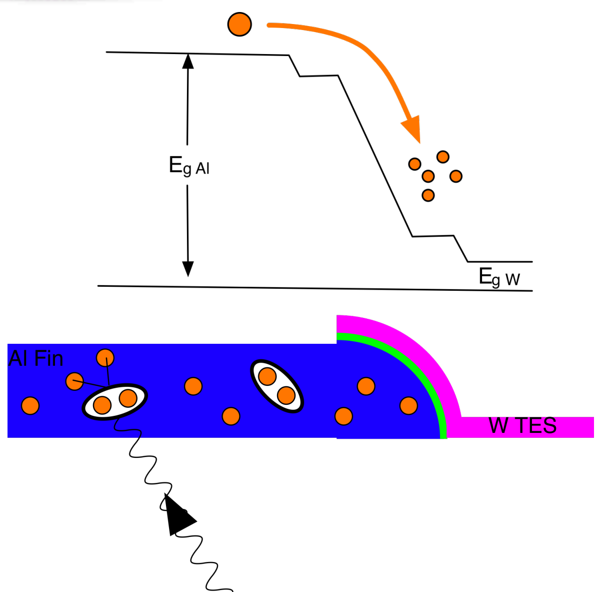
Athermal Phonon Sensors

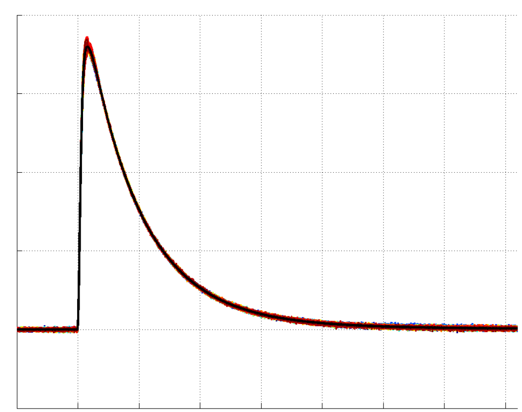




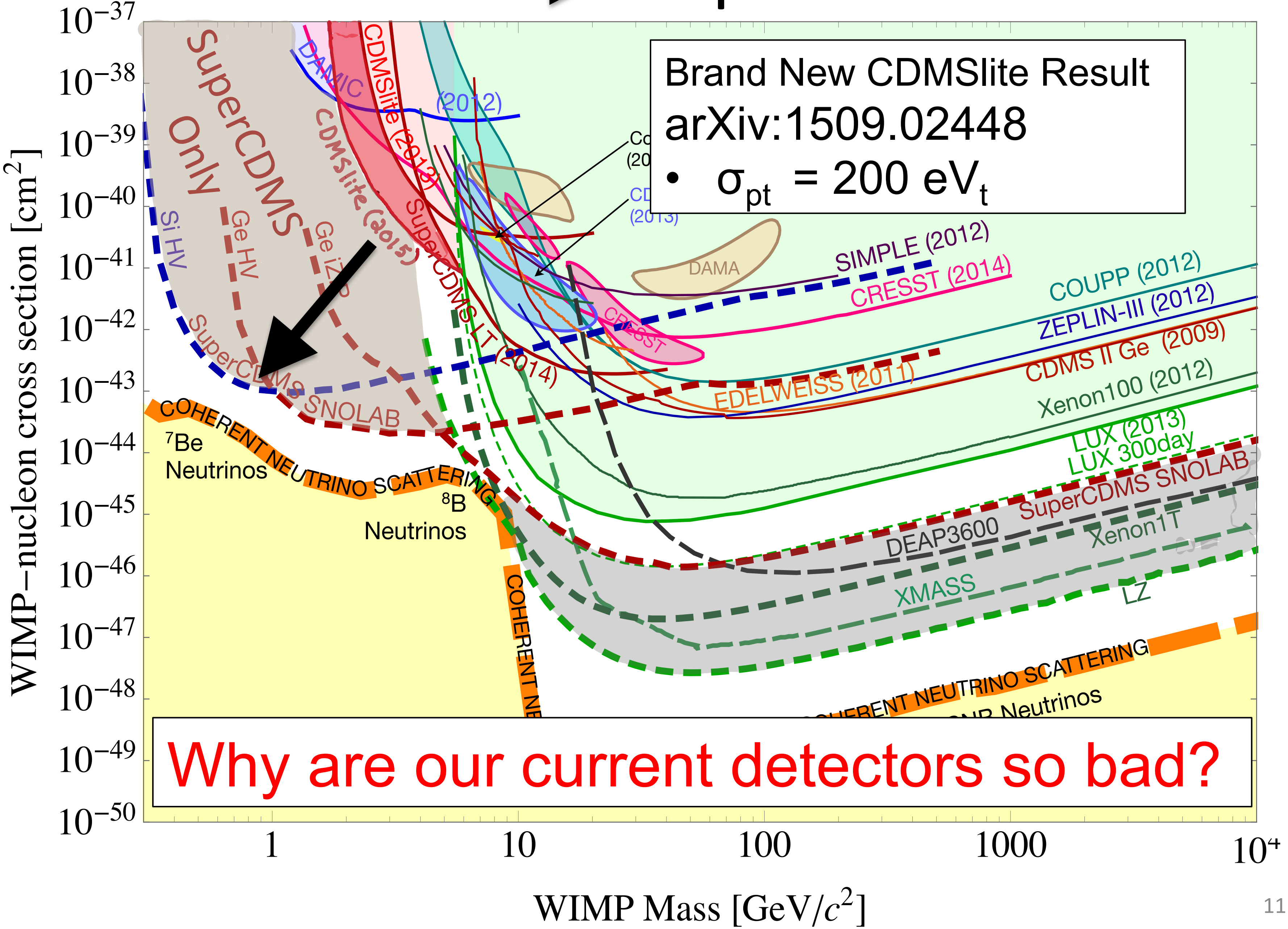
Collect and Concentrate Phonon Energy into W TES (Transition Edge Sensor)





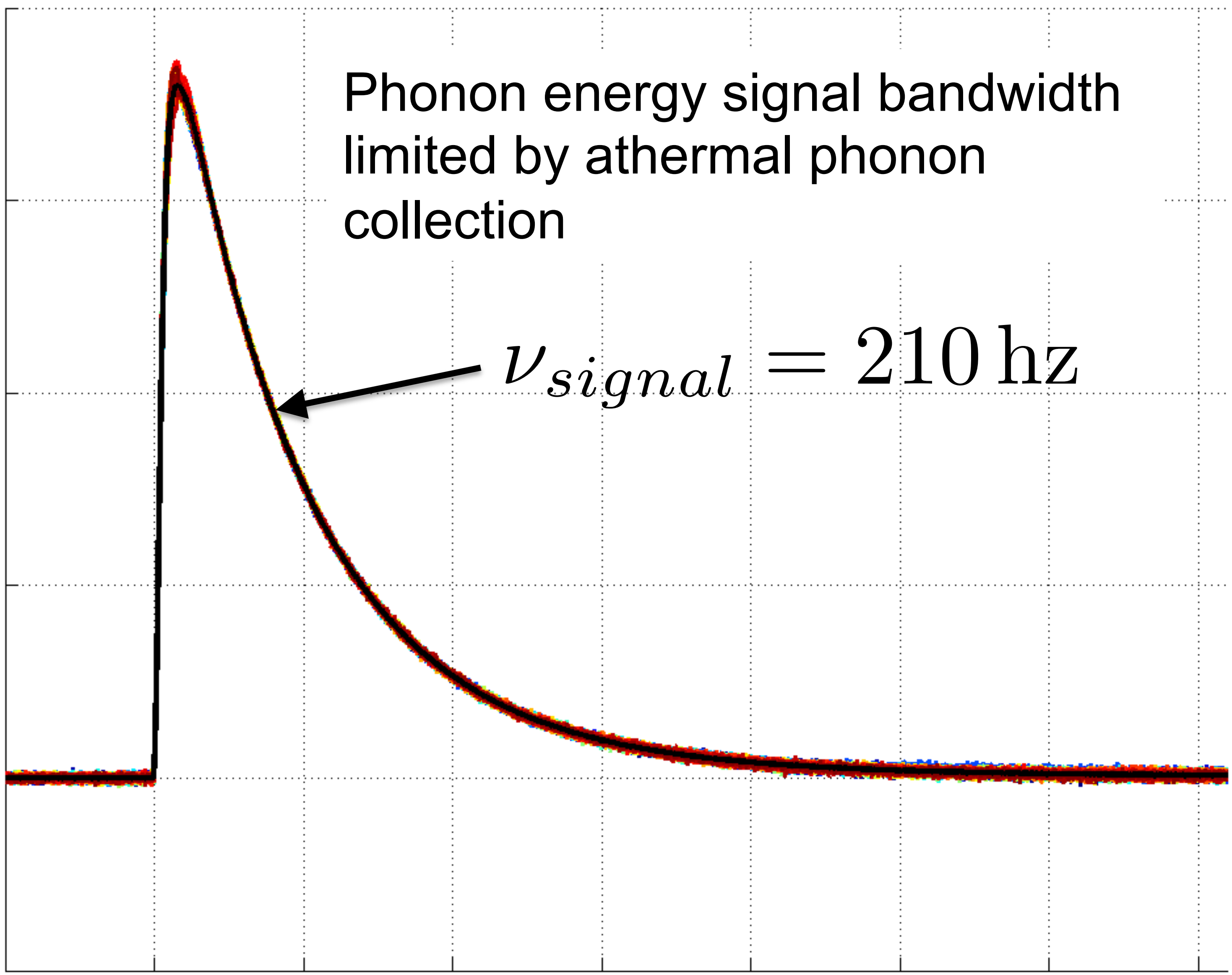


CDMSlite → SuperCDMS SNOLAB

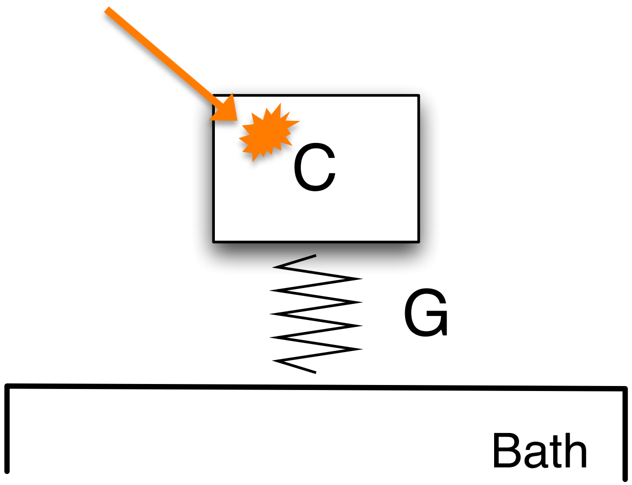


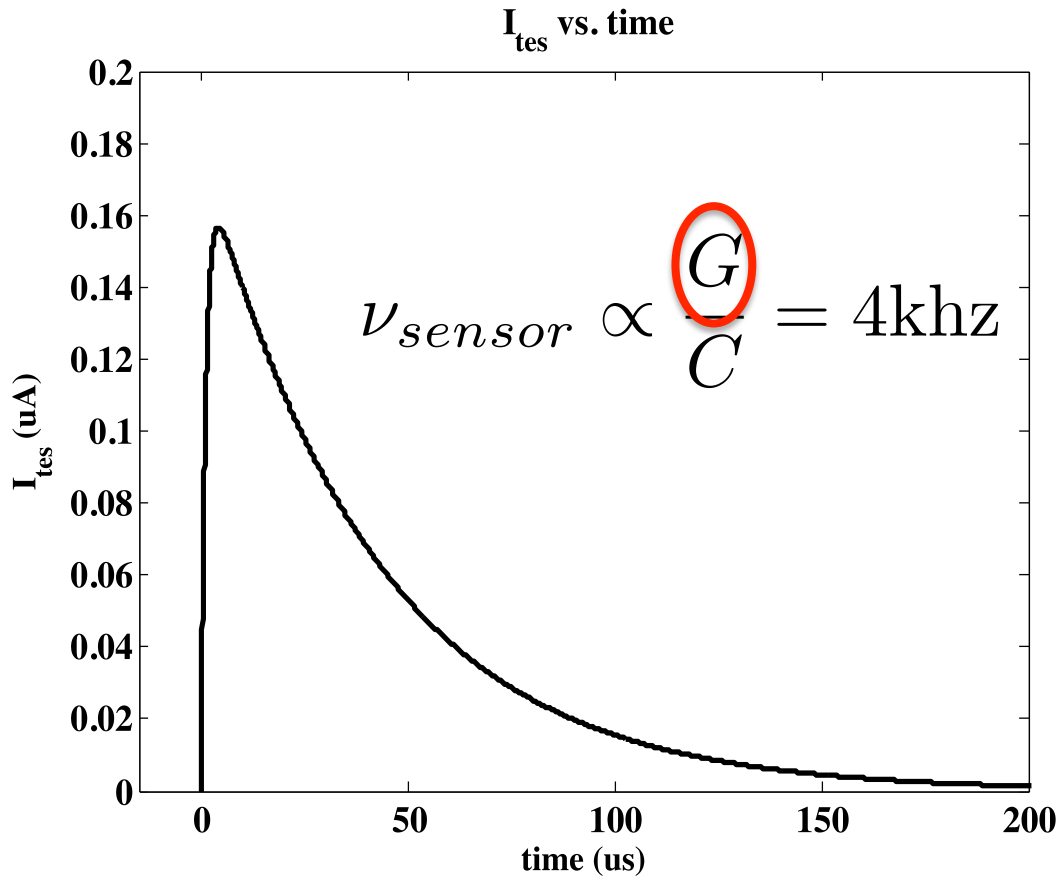
Why are our current detectors so bad?

Phonon Signal Bandwidth



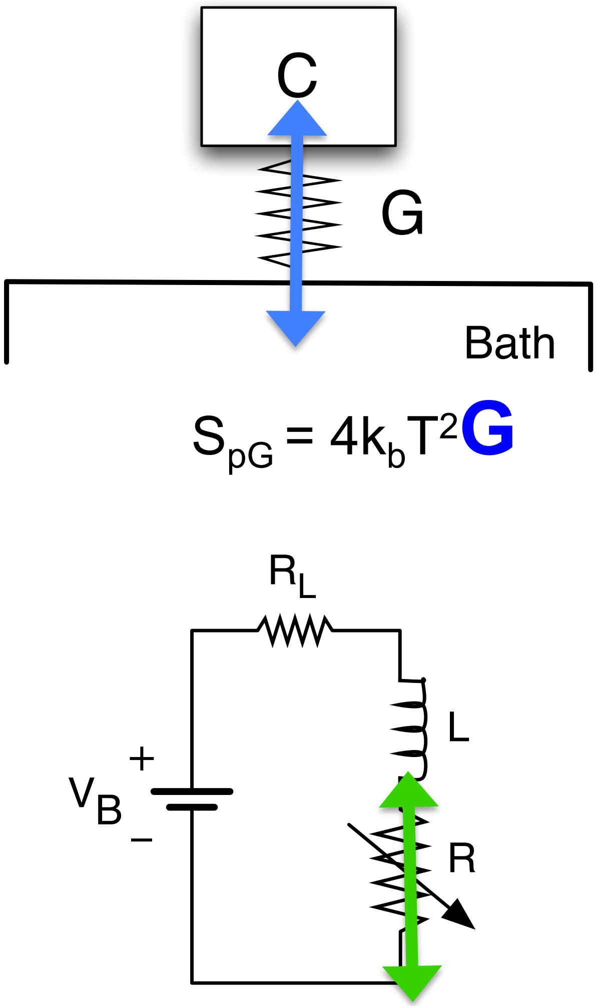
Transition Edge Sensor: Dynamics



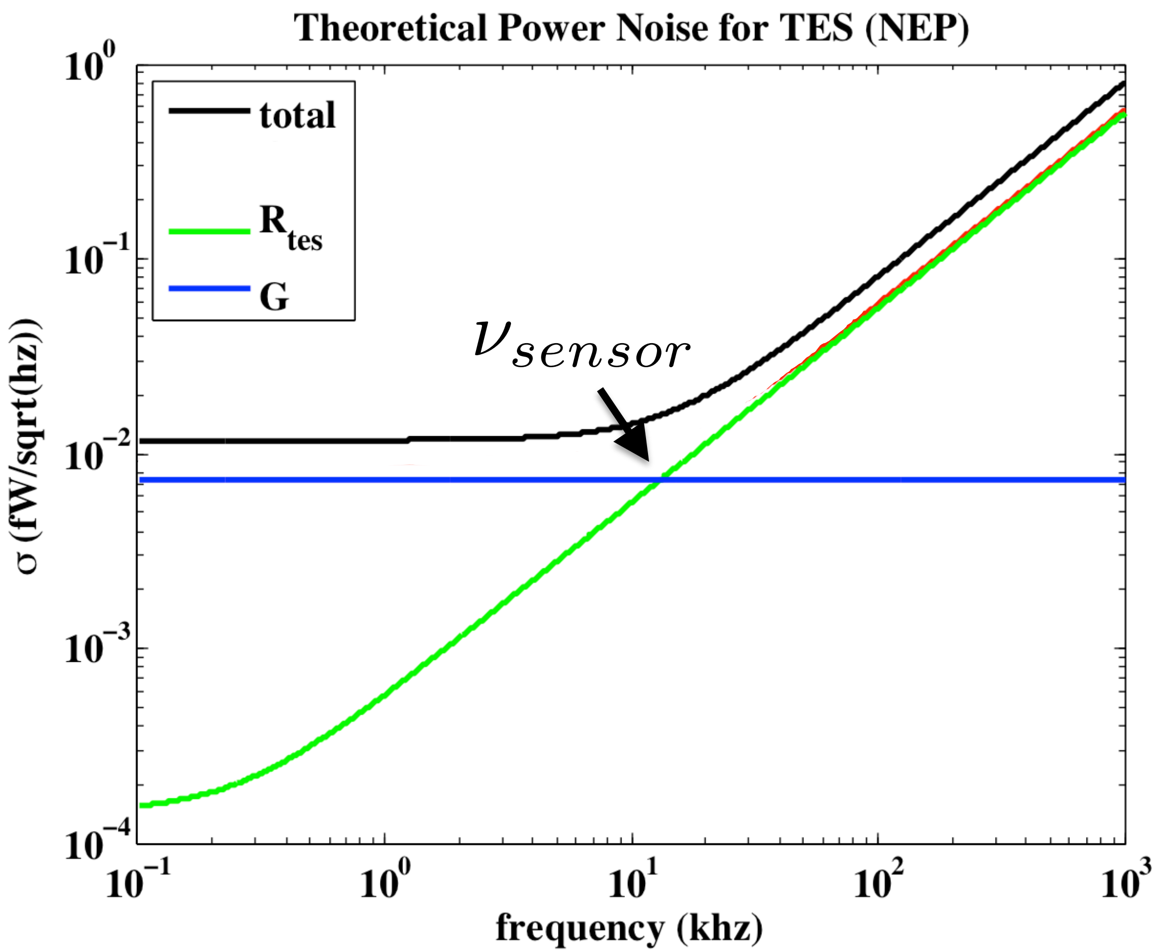


$$\nu_{signal} << \nu_{sensor}$$

Transition Edge Sensor: Noise



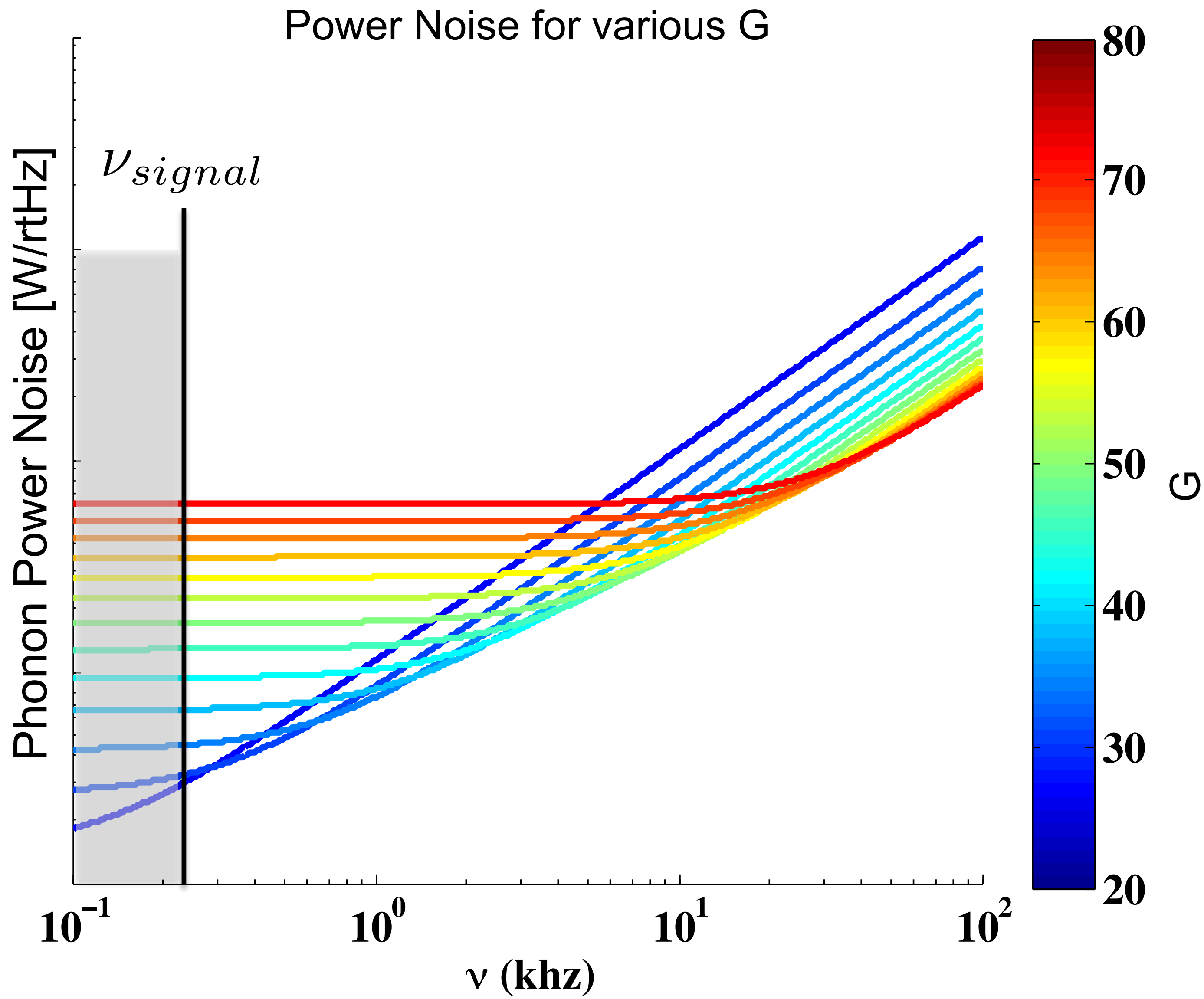
$S_{pG} = 4k_bT^2\mathbf{G}$



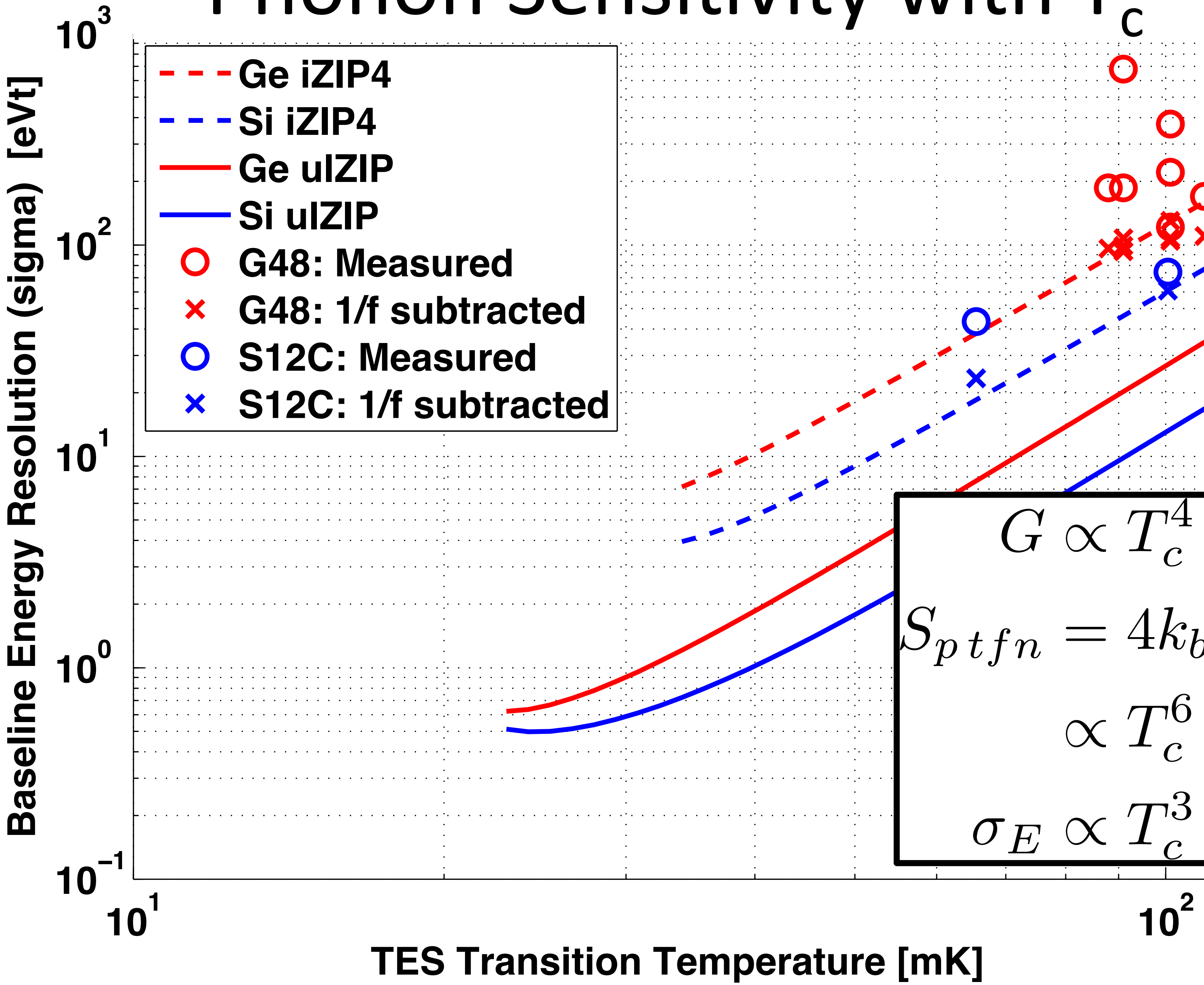
DC noise scales with G

Bandwidth Optimization Rule

$$\nu_{sensor} < \nu_{signal}$$



Phonon Sensitivity with T_c



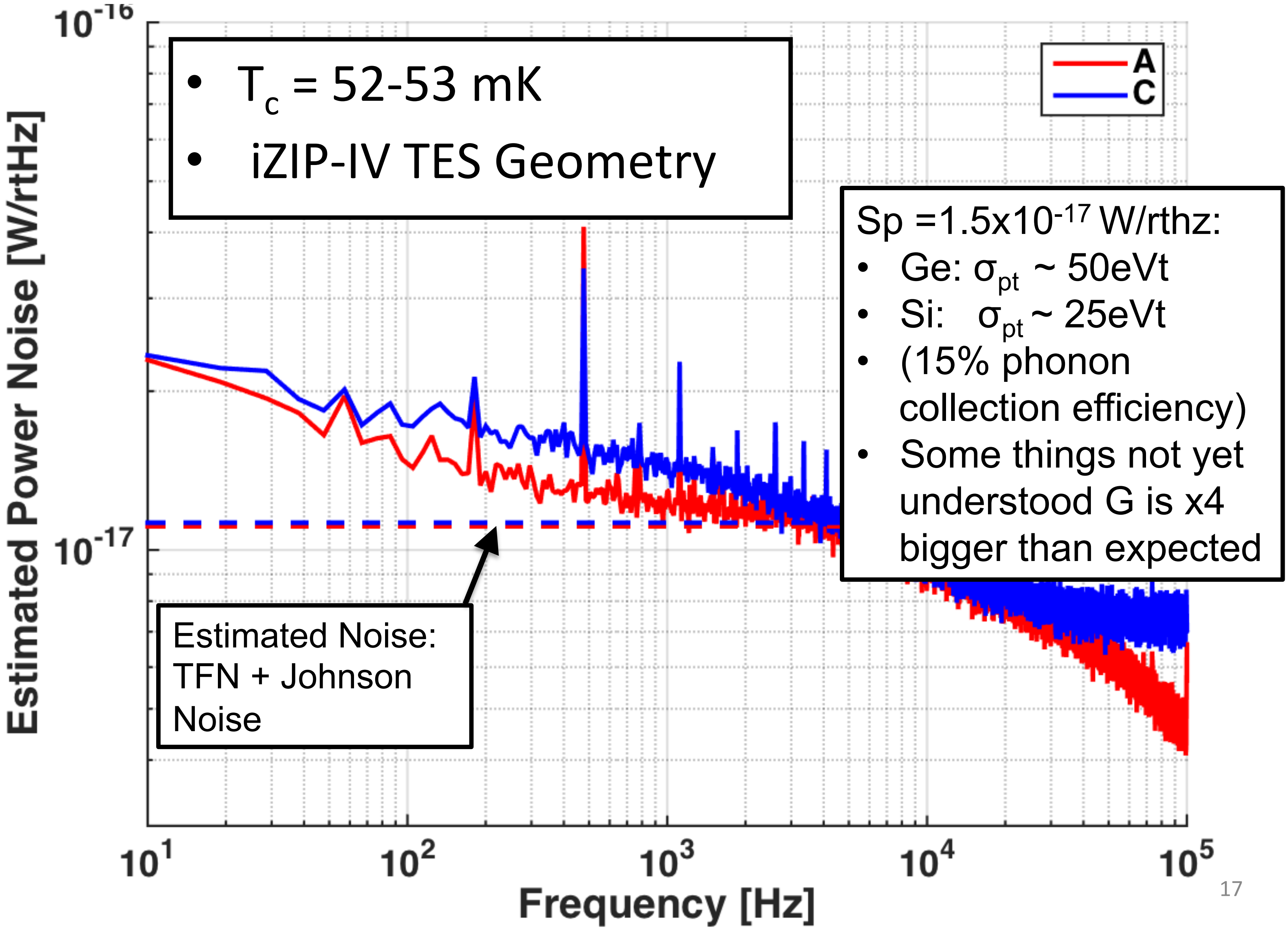
$$G \propto T_c^4$$

$$S_{ptfn} = 4 k_b T_c^2 G$$

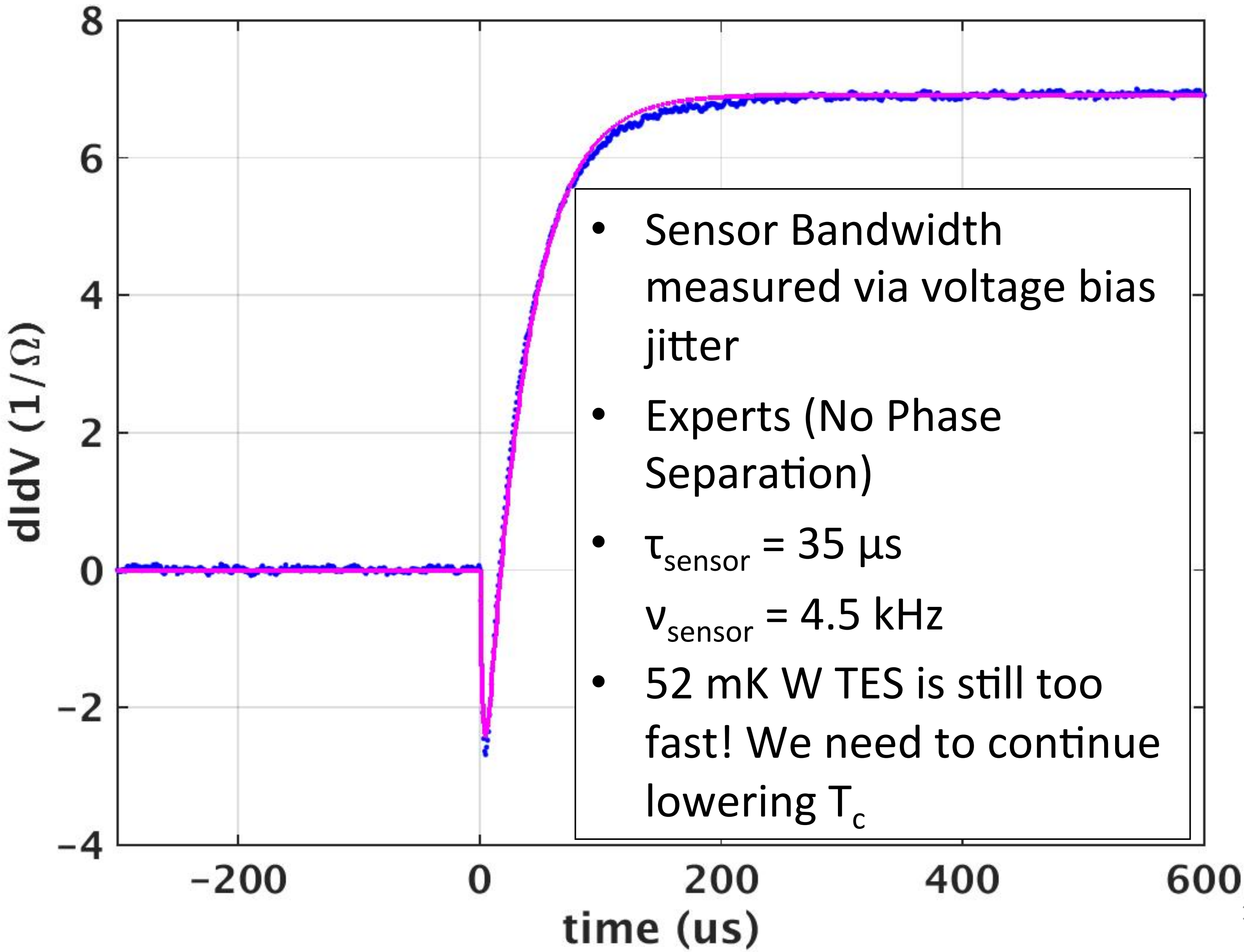
$$\propto T_c^6$$

$$\sigma_E \propto T_c^3$$

New: Noise of G23R Test Device

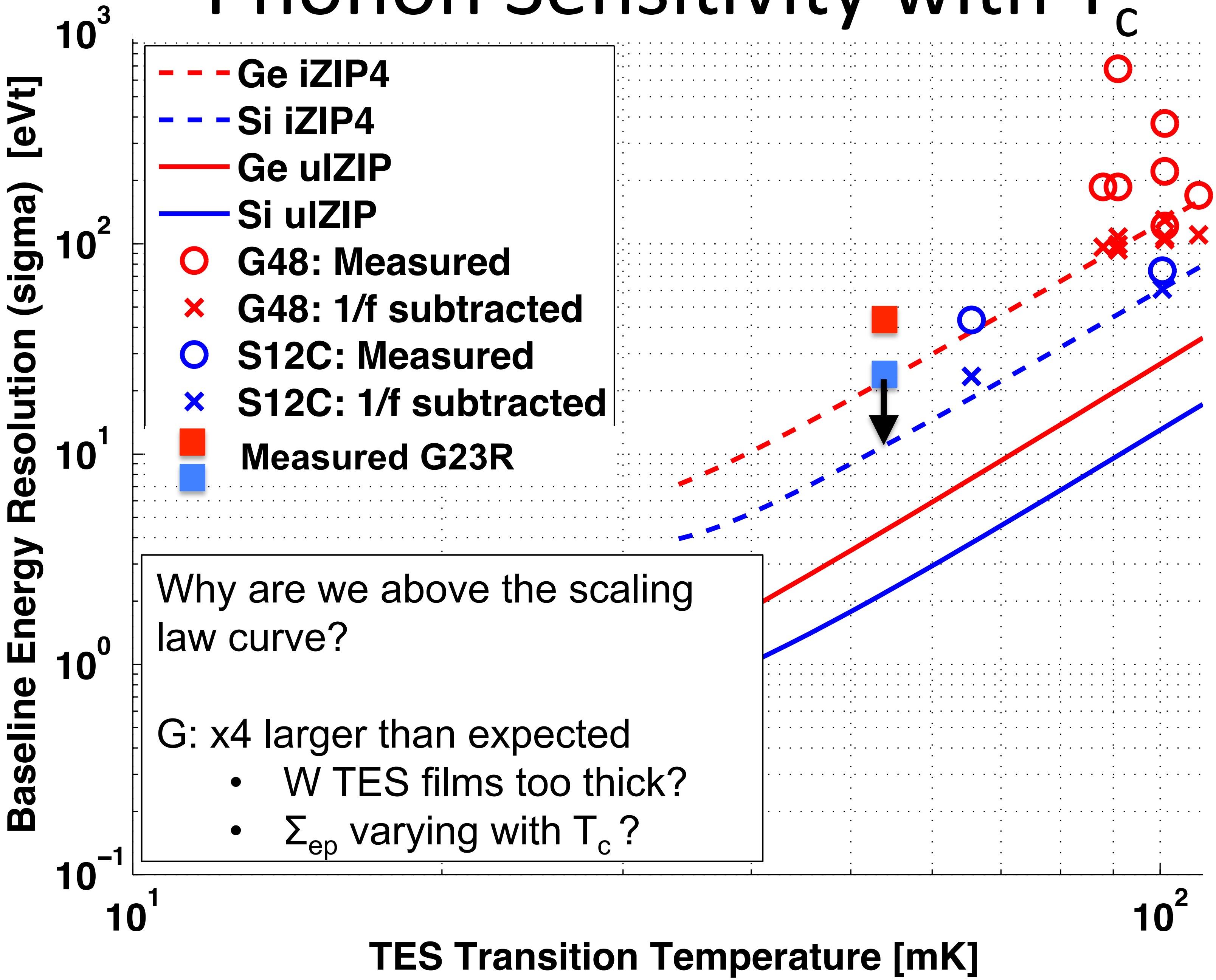


New: G23R Sensor Bandwidth



- Sensor Bandwidth measured via voltage bias jitter
- Experts (No Phase Separation)
- τ_{sensor} = 35 μs
  ν_{sensor} = 4.5 kHz
- 52 mK W TES is still too fast! We need to continue lowering T_c

Phonon Sensitivity with T_c



Why are we above the scaling law curve?

G: x4 larger than expected

- W TES films too thick?
- Σ_{ep} varying with T_c ?

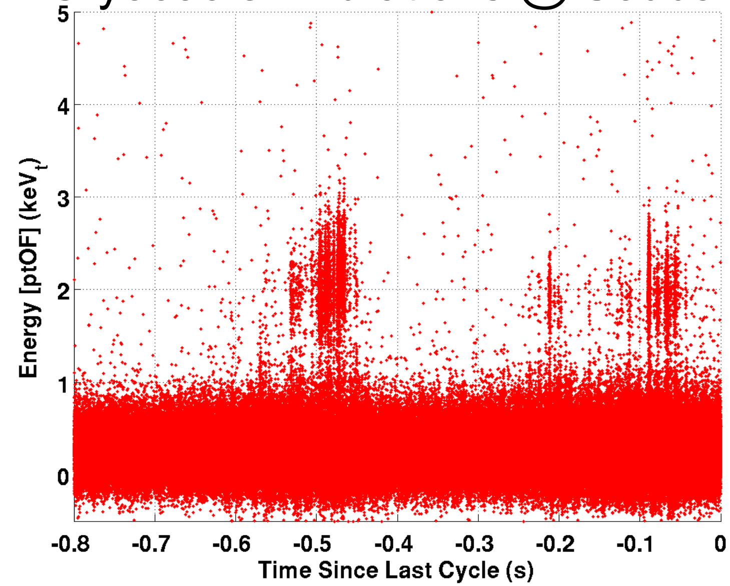
Why is it taking so long?

What are the fundamental limits in phonon resolution?

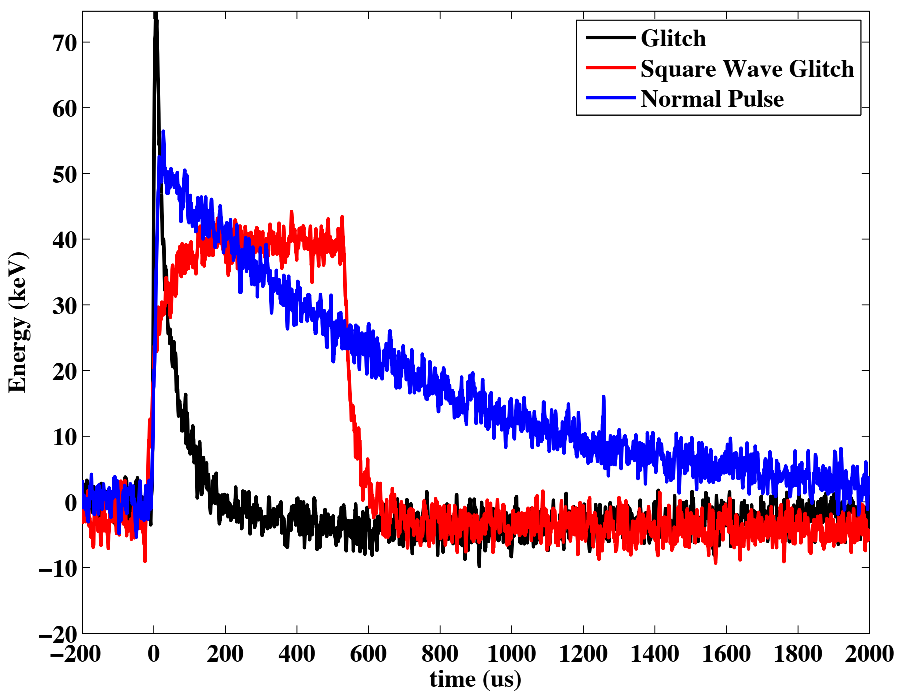
Problem #1: Parasitic Power

As we lower T_c, we become more sensitive to nuclear recoils, but we also become more sensitive to environmental noise

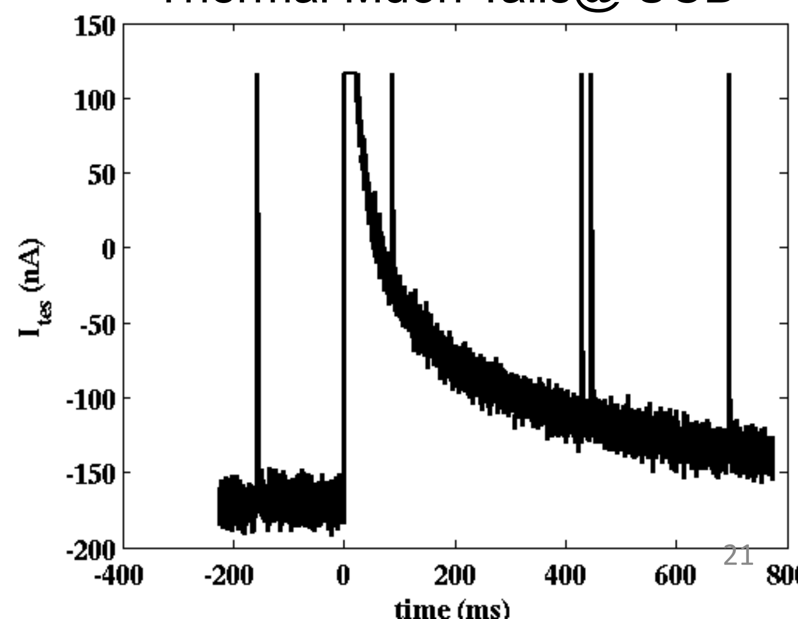
Cryocooler Vibrations @ Soudan



EMI Interference @ UCB

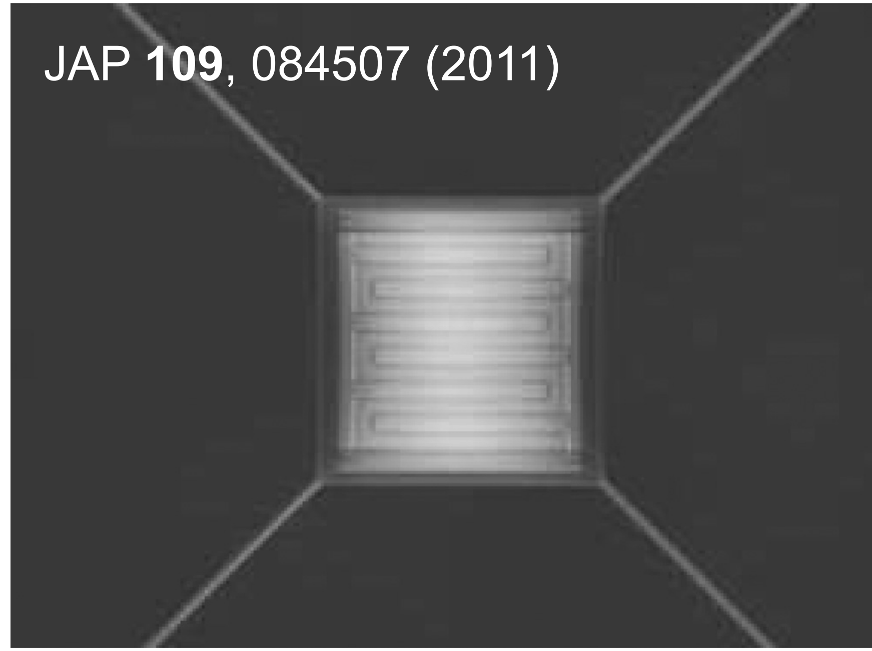


Thermal Muon Tails@ UCB



Resolution Limits: Parasitic Power

SAFARI has created devices with x75 smaller G & x9 smaller P_{bias} than we require

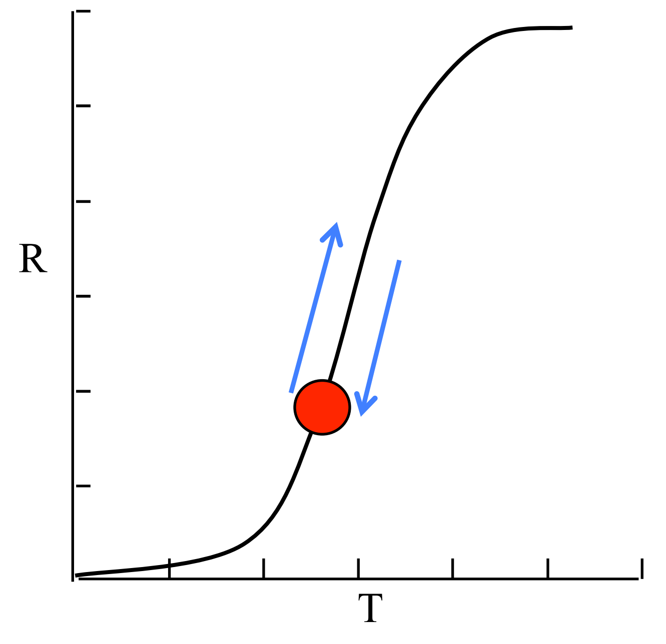


	SuperCDMS (modeled)	SAFARI (measured)
Tc	30 mK	111 mK
G	12800 fW/K	170 fW/K
P_{bias}	76 fW	8.9 fW
S_{NEP}	$6x10^{-19}$ W/rthz	$4.2x10^{-19}$ W/rthz

We're far from the fundamental limits on phonon resolution due to parasitic power

Problem #2: W TES Sensitivity Degradation at low T_c?

- As we continue to lower T_c, does the W TES lose sensitivity? Does it become impossible to fabricate?
- Who knows?
- 100mK -> 50mK sensitivity remained invariant
- If yes, there are lots of other TES material out there



Problem #3: Base Temperature

- Dilution Fridge base temperature < ~70% T_c
- Short Term: Definitely an issue for SuperCDMS
  - UCB 75uW: 35 mK
- Long Term: Shouldn't be a problem
  - New DF at UCB (10mK)

Summary

- Light mass dark matter detectors need amazing energy resolution
- Ultra sensitive calorimeters:
  - very low T
  - Small sensor volumes -> collection / concentration
  - Final Ingredient: Bandwidth matching
- Over the next 5 years, there should be huge improvements in detector performance
  - 1eV baseline noise
  - ER/NR discrimination for sub-keV recoils